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EARTHQUAKE RECURRENCE RATES AND PROBABILITY ESTIMATES FOR THE OCCURRENCE OF SIGNIFICANT SEISMIC ACTIVITY IN THE CHARLESTON AREA: THE NEXT 100 YEARS

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ABSTRACT

The characteristics of the decay in the frequency of earthquakes following the August 31, 1886 Charleston, S.C. earthquake suggest that the aftershock sequence of this event lasted through 1892. Subsequent seismicity appears to represent a new seismic cycle independent of the 1886 shock. The frequency - epicentral intensity relation of seismicity occurring during the period 1893-1984 suggests that the recurrence interval of Modified Mercalli intensity X earthquakes similar to the 1886 Charleston event is about 1600 years. The recurrence interval of intensity VII events is found to be about 85 years. Assuming a Poisson frequency distribution, the probability of an intensity X earthquake occurring within the next 100 years (1986-2086) is about 6 percent. However, the probability of a moderate earthquake of epicentral intensity VII occurring within the next 100 years is about 70 percent.

INTRODUCTION

A Modified Mercalli Intensity X earthquake occurred near Charleston, South Carolina on August 31, 1886. This is the largest historical earthquake to occur in the southeastern United States and although smaller than the New Madrid earthquakes of 1811-1812, its proximity to populated areas made it the most destructive U.S. earthquake in the 19th century. A critical element in assessing seismic hazard in this region is an estimate of the probability of similar large potentially destructive earthquakes occuring in the near future. This investigation is designed to provide such an estimate.

Some investigators have speculated that most, if not all, of the Charleston earthquakes recorded since 1886 are aftershocks of the 1886 event [Ref. 1]. If this is true, the earthquake frequency-intensity distribution of the last 100 years may not be representative of long term frequency distribution of earthquakes in the area. Consequently, the

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initial task of this study was to establish the duration of the aftershock sequence of the August 31, 1886 earthquake. This was accomplished by modeling the frequency of seismicity following the 1886 event with an Omori type decay function. Next the least squares method was used to develop an updated frequency - epicentral intensity relation for subsequent historical seismicity occurring in the Charleston area. Based on this relationship, the recurrence intervals for Modified Mercalli intensity V through X events were estimated. Finally, a Poisson distribution function was fit to these new recurrence estimates to assess the probability of 1) the occurrence of an intensity X event similar to the 1886 event within the next 100 years (1986 - 2086) and 2) the occurrence of an intensity VII event similar to the 1912 Charleston-Summerville event during this same time period.

There are two basic assumptions in this investigation. First we assume that the frequency - epicentral intensity distribution of seismicity occurring in the Charleston area (exclusive of the 1886 event and its aftershocks) is linear, and can be used to estimate the recurrence interval of similar rare large events. This assumption is based on investigations of active fault zones in both interplate [Ref. 2] and intraplate [Ref. 3] regions. However, we recognize that there are some instances where this assumption may not be valid. Second, to simplify probability calculations, we assume that the recurrence interval distribution of earthquakes in the intensity range of interest can be modeled using a Poisson frequency distribution function. To better understand the limitations associated with this simplification, the resulting probabilities are qualitatively compared to those expected using lognormal, Gaussian and Weibull frequency distribution functions.

RESULTS

Duration of 1886 Aftershock Sequence

Generally, the rate of aftershocks following large shallow crustal earthquakes decreases with time. The frequency of aftershock occurrence is related to the time after the mainshock by a formula such as:

$$N(t) = A\ t^{-p} \tag{1}$$

where $N(t)$ is the frequency of aftershocks, A and p are constants and (t) is the time after the mainshock. This type of decay function is commonly referred to as an Omori decay function and has been used to define the duration of aftershock sequences [Ref. 4]. For example, Page [Ref. 5] studied the aftershock sequence of the 1964 Alaska earthquake and found the constant value for p of 1.14. He also found that the value of p did not appear to vary significantly from one aftershock sequence to another or from one tectonic setting to the next. Ellsworth and others [Ref. 6] evaluated the aftershock sequence of the 1906 San Francisco earthquake and found that the decay in the frequency of aftershocks following the

1906 mainshock through 1910 yielded a value of p = 1.0. Subsequent to 1910 the frequency of earthquakes was found to be greater than predicted by this equation and the authors concluded that seismicity after 1910 represented a new cycle of seismicity independent of the 1906 event.

In this investigation the seismicity following the August 31, 1886 Charleston event was modeled in a similar fashion. The plot of earthquake frequency vs time following the 1886 mainshock is presented on Fig. 1. As shown, the frequency of earthquake activity follows an Omori type decay curve from 1886 through 1892. The line line through the data represents a value of p=1.0, similar to the value found for the aftershock sequences discussed above. Subsequent to 1892 the level of

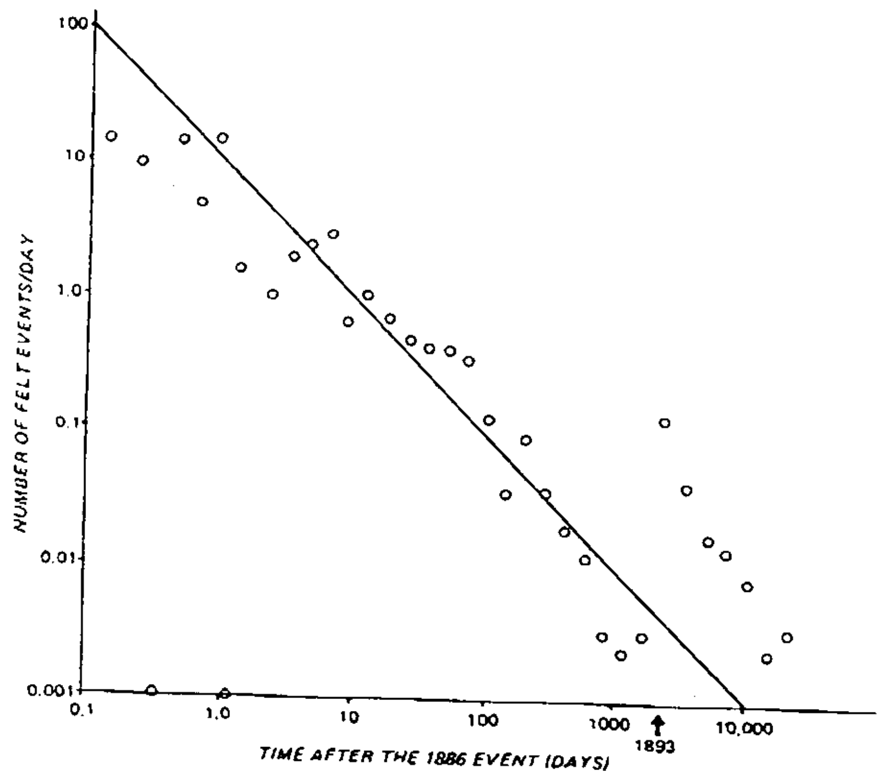

Figure 1. Decay in the frequency of earthquakes following the 1886 mainshock. The line through the data represents a value of $p = 1.0$ (see EQ. 1). Note that seismicity occuring subsequent to 1892 falls well above this line, suggesting that it is independent of the 1886 event.

seismicity exceeds that predicted by the decay of the previous years, suggesting that the latter seismicity represents a new cycle of seismicity independent of the 1886 event. Based on evaluation of newspaper reports Seeber and Armbruster [Ref. 10] reached a similar conclusion.

Earthquake Frequency - Epicentral Intensity Relation

The distribution of earthquake frequency vs earthquake size is generally represented as an exponential distribution where the number of events decreases as earthquake size increases [Ref. 11]. Where epicentral intensity data is the primary estimate of earthquake size, the most common representation of this exponential distribution is the relationship:

$$\log N_c = a - b\, I_{(o)} \qquad (2)$$

In EQ. 2, the term N_c refers to the number of earthquakes occurring during a specified time period greater than or equal to epicentral intensity I_o. For this investigation N_c has been normalized to represent events per year occurring in the Charleston area. The constant "a" denotes the zero magnitude intercept on a semilog plot and provides an indication of the overall level of activity, while the constant "b" provides information regarding the relative proportion of small to large events.

Both linear regression and maximum likelihood techniques are commonly used to determine the constants a and b. Each technique has its own advantages and disadvantages which are discussed at length in the literature, (for example Ref. 12). However, as noted by Johnston and Nava, [Ref. 13], the maximum likelihood method places so little weight on larger events it is generally less suited for estimating "b" for long term seismic hazard studies. Consequently, the least squares method is used in this study.

The plot of the cumulative number of events N_c/year vs epicentral intensity I_o occurring in the Charleston area for the period 1893-1984 is shown in Fig. 2. Felt events which were not assigned an intensity in the references mentioned in the figure caption are included as "intensity II". Data down to and including intensity IV defines a linear trend. However, below intensity IV the reported number of event falls below the trend, suggesting that the data are probably incomplete for these lower intensities. The annual frequency - epicentral intensity relation determined using the least squares method for the data shown in Fig. 2 is:

$$\log N_c = 1.02 - 0.42\, I_o \qquad (3)$$

Earthquake Recurrence Intervals

If the overall rate of seismicity in the Charleston is temporally stable, then EQ.3 suggests the recurrence intervals presented in Table I.

TABLE 1
EARTHQUAKE RECURRENCE INTERVALS

Epicentral Intensity (MM)	Recurrence Interval (yrs)
V	12
VI	32
VII	83
VIII	219
IX	575
X	1585

Recently Obermeier and others [Ref. 16] and Talwani and Cox, [Ref. 17], have carried out investigations of deformed features preserved in sediments associated with prehistoric earthquakes in the Charleston area. On the basis of preserved liquefaction features these investigators suggest that the Charleston area has been the site of at least one large pre-1886 event and probably two such earthquakes in the last several thousand years. On the basis of C14 age dating of material cross cutting extruded sands, Talwani and Cox [Ref. 17] suggest the maximum recurrence interval to be in the range of 1500-1800 years for earthquakes similar to the 1886 event. This range is consistent with the estimate obtained from the recurrence relation developed in this study.

Probability of Future Large Earthquakes

In terms of seismic hazard, a more important question than "what is the recurrence interval of large events" is "what is the likelihood of an event similar to the 1886 event occurring in the near future." As discussed by Johnston and Nava, [Ref. 13], to address this issue requires some idea of the frequency distribution of recurrence intervals for the intensity of interest in addition to an estimate of the earthquake recurrence intervals. In other words, over a time span much greater than the recurrence interval of 1585 years, what is the variation about this value? For example, if two intensity X events occur separated by a 100 year interval and then a third event occurs 2900 years later, the average recurrence interval frequency distribution would be much different than the frequency distribution of a sample including three events each occurring 1500 years apart.

Several different frequency distributions have been used in the literature to determine the probability of future large earthquakes. These include the Poisson [Ref. 18], Gaussian and lognormal [Ref. 19], and Weibull [Ref. 20] frequency distributions. For simplicity the Poisson distribution is used in this study and the results qualitatively compared to those that would be expected using the other three frequency distribution functions mentioned above.

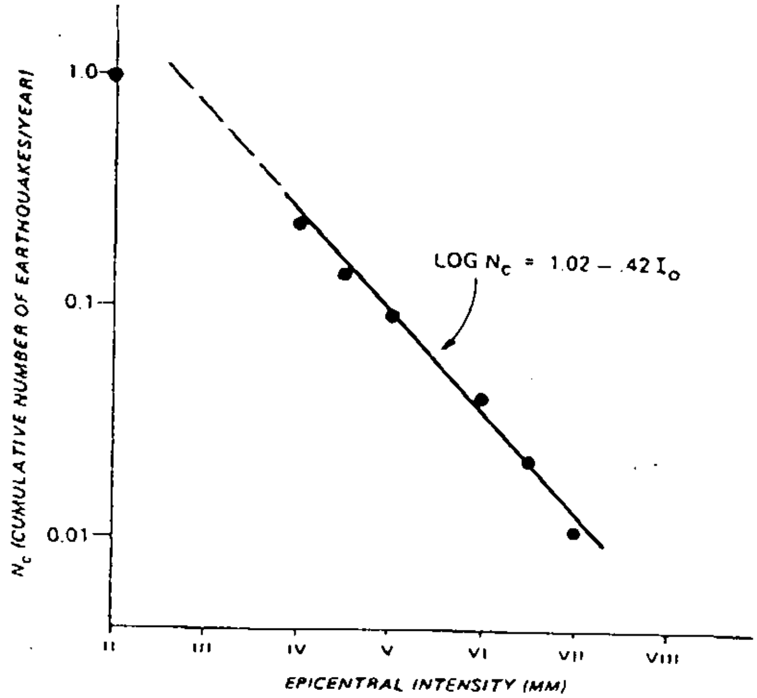

Figure 2. Cumulative frequency-epicentral intensity data base for determining Gutenburg-Richter constants a and b. Macroseismic earthquakes occuring in the period 1893-1984. Compiled from Ref. 7, 8, and 9.

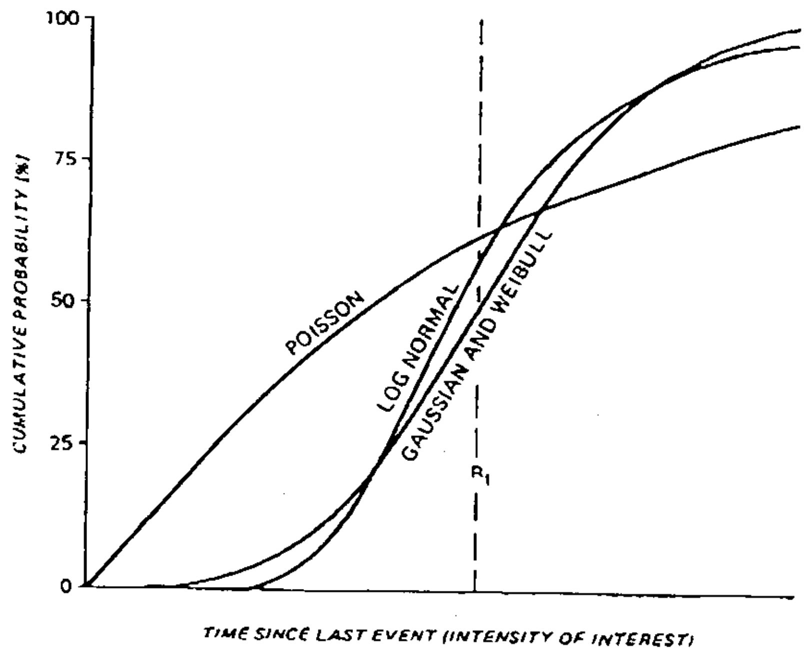

Figure 3. Comparison of Cumulative Probability determined for various frequency distributions. In cases where the time since the last event of interest is less than its recurrence interval (R_I) curves to the left of the vertical line apply (such is the situation for Case 1 of this study). In cases where the time since the last event of interest is greater than its recurrence interval, curves to the right of the vertical line apply (such is the situation for Case 2 of this study).

Assuming a Poisson frequency distribution, the probability (P) for an earthquake with a recurrence interval of (R_I) occurring during a time interval (Δt) can be expressed as

$$P(\Delta t) = 1 - e^{-\Delta t/RI} \quad (4)$$

In this study the probability was determined for two cases:

Case 1 - the occurrence of an intensity X event similar to the 1886 event within the next 100 years (1986 - 2086).

Case 2 - the occurrence of an intensity VII event similar to the 1912 Charleston-Summerville event during this same time period.

The resulting probabilities are 6 percent and 70 percent for Cases 1 and 2 respectively.

It should be pointed out that for a given Δt in EQ.4 the probability of occurrence is independent of the time that has passed since the last event. Because of this, probability estimates where the sum of the time elapsed since the last event of recurrence interval (R_I) and time window of interest (Δt) is less than the recurrence interval (R_I) may tend to represent upper bound estimates. Conversely, in cases where the sum of the time elapsed since the last event with an recurrence interval of (R_I) and a time window of interest (Δt) exceeds the recurrence interval, probability estimates determined assuming a Poisson distribution may tend to underestimate the seismic hazard. These points are illustrated schematically in Fig. 3.

SUMMARY

The largest historical earthquake (Modified Mercalli intensity X) in the southeastern United States occurred near Charleston, South Carolina on August 31, 1886. Critical elements in assessing the seismic hazard in this region are estimates of the recurrence rates of large potentially destructive earthquakes similar to this event and the probability of their occurrence in the near future. To this end, a frequency - epicentral intensity relation was derived for seismicity occurring in the Charleston area. The resulting relation ($\log N_c = 1.02 - 0.42\ I_o$) is based on macroseismic data for the years 1893 through 1984. This time period was chosen so as to exclude the 1886 event and it's aftershocks.

If the overall rate of seismicity in the Charleston does not vary with time, then this relation suggests a recurrence interval of 1585 years for an intensity X event. This value is consistent with the results of recent paleoliquefaction investigations which suggest the maximum recurrence interval in the Charleston area for earthquakes similar to the 1886 event to be in the range of 1500-1800 years.

Based on these new earthquake recurrence rates, the probability of future large earthquakes in the Charleston area was determined. Results indicate that the probability of a Modified Mercalli intensity X similar to the 1886 event occurring within the next 100 years (1986-2086) is low. The upper bound estimate, which is based on the assumption of a Poisson frequency distribution of recurrence intervals, is 6%. Estimates based on frequency distributions, which take into account the 100 years that have passed since the 1886 event, would yield lower probabilities.

While the likelihood of an event similar to the 1886 Charleston earthquake is low, the probability of a moderate earthquake of epicentral intensity VII occurring within the next 100 years was determined to be greater than 70 percent. Such an event would be similar to the Charleston - Summerville earthquake of June 12th, 1912. This event was associated with Modified Mercalli intensity IV-V levels of ground motion in the Piedmont of South Carolina and the eastern Coastal Plain of Georgia and caused some damage in the epicentral area.

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